

Against all odds? Forming the planet of the HD196885 binary

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Abstract HD196885Ab is the most "extreme" planet-in-a-binary discovered to date, whose orbit places it at the limit for orbital stability. The presence of a planet in such a highly perturbed region poses a clear challenge to planet-formation scenarios. We investigate this issue by focusing on the planet-formation stage that is arguably the most sensitive to binary perturbations: the mutual accretion of kilometre-sized planetesimals. To this effect we numerically estimate the impact velocities dv amongst a population of circumprimary planetesimals. We find that most of the circumprimary disc is strongly hostile to planetesimal accretion, especially the region around 2.6AU (the planet's location) where binary perturbations induce planetesimal-shattering dv of more than 1km.s^{-1} . Possible solutions to the paradox of having a planet in such accretion-hostile regions are 1) that initial planetesimals were very big, at least 250km, 2) that the binary had an initial orbit at least twice the present one, and was later compacted due to early stellar encounters, 3) that planetesimals did not grow by mutual impacts but by sweeping of dust (the "snowball" growth mode identified by Xie et al., 2010b), or 4) that HD196885Ab was formed not by core-accretion but by the concurrent disc instability mechanism. All of these 4 scenarios remain however highly conjectural.

Keywords Planetary systems · Binary Stars

1 Introduction

1.1 Planets in binaries

Studying planet formation in binaries is of fundamental importance, as a majority of main sequence stars are members of multiple systems (Duquennoy and Mayor, 1991). Moreover, planets in binaries are no longer theoretical concepts, as about

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20% of all known exoplanets have been found to inhabit multiple stellar systems (Desidera & Barbieri, 2007; Mugrauer & Neuhäuser, 2009). Most of the planet-bearing binaries have large separations, often in excess of 1000 AU, for which the influence of the companion star on the planet region, and the planet formation process, is probably limited. However, a handful of planets inhabit much tighter binaries, which separations as small as ~ 20 AU: Gl86, with a planet at 0.11 AU and a companion at 18.4 AU (Queloz et al., 2000; Lagrange et al., 2006), HD 41004 with a planet at 1.64 AU and companion at 23 AU (Zucker et al., 2004) and γ Cephei, for which the planet lies at 2.04 AU and the companion at 20.18 AU (Hatzes et al., 2003; Neuhäuser et al., 2007). For these systems (especially 41004 and γ Cephei), the closeness of the companion must have had an influence on the way the planet formed and dynamically evolved. Studying how such planets came about is of great interest, all the more because close-binaries can be used as a test bench for planet formation models, by confronting them to an unusual environment where some crucial parameters might be pushed to extreme values.

Historically, the first issue that has been investigated is that of the long term stability of planetary orbits in binaries. The reference work on this issue remains probably that of Holman & Wiegert (1999), who derived empirical expressions for orbital stability as a function of binary semi-major axis a_B , eccentricity e_B and mass ratio μ . Later studies have shown that, reassuringly, all known exoplanets in multiple systems are on stable orbits (e.g. Dvorak et al., 2003; Haghighipour et al., 2010), although the case for HD41004 is not fully settled yet, as it depends on the yet unconstrained eccentricity of the binary orbit (Haghighipour et al., 2010).

1.2 Planet formation in binaries

The next step is to study under which condition such planets can *form*, as the constraints for planet formation might be very different from those for orbital stability. This issue is a much more difficult one. Planet formation is indeed a very complex process, believed to be the succession of several stages (e.g. Lissauer, 1993), each of which could be affected in very different ways by the perturbations of a secondary star. Not surprisingly, the effect of binarity on each of these different stages is usually investigated in separate studies.

The initial phase of planet formation, i.e., the formation and evolution of a gaseous protoplanetary disc, has been investigated early on by Artymowicz & Lubow (1994) and Savonije et al. (1994), who have shown that the circumprimary disc is tidally truncated by the companion. This truncation occurs at a location comparable to the outer limit for dynamical stability and thus safely lies beyond the position of all detected exoplanets. It could nevertheless pose a problem, especially for giant planet formation, as it deprives the disc from a large fraction of its mass. For the specific case of γ Cephei, however, Jang-Condell et al. (2008) have found that there is probably enough mass left in the truncated disc to form the observed giant planet. But another, potentially more troublesome consequence of disc truncation is that it shortens the viscous lifetime of the disc, and thus the timespan for gaseous planet formation. This effect seems to have been observationally confirmed by Cieza et al. (2009), who

found that young binaries with separation ≤ 100 AU have a lower probability of hosting circumstellar dust in the innermost few AU around each star (Duchêne, 2010), even if some close binaries do show signs of a hot circumprimary disc.

The next stage of planet formation, the condensation of small grains and their growth into larger pebbles and eventually kilometre-sized planetesimals, has not been extensively studied in the context of binary systems. One main reason is probably that this stage is the one that is currently the least understood even in the "normal" context of single stars (e.g. Blum & Wurm, 2008), so that extrapolating it to perturbed binaries might seem premature. A noteworthy exception is the study by Nelson (2000) showing that for an equal-mass binary of separation 50 AU, temperatures in the disc might stay too high to allow grains to condense. But, as acknowledged by the author himself, these results are still preliminary and a full study of this issue has yet to be undergone. Very recently, Zsom et al. (2011) showed that, even if grains can condense, binary perturbations might impend their growth by mutual sticking because of too high impact velocities.

The stage for which the influence of a companion is probably best understood is the final step of planetary accretion, leading from Lunar-sized embryos to fully formed planets. Several studies have shown that the regions where embryo accretion can proceed roughly correspond to those for orbital stability (Barbieri et al., 2002; Quintana et al., 2007; Guedes et al., 2008; Haghighipour et al., 2010). This is a further reassuring result for all known exoplanets-in-binaries, in particular the archetypal case that is γ Cephei, for which the extensive study of Kley & Nelson (2008) showed that, *if* embryos can form around 2 AU from the primary, then they can evolve to form planetary cores at the present planet location.

1.3 Planetesimal accretion in binaries: latest results

The stage that has been the most extensively studied in recent years is the one just before the final embryos-to-planets phase, i.e., the one leading, through mutual accretion of kilometer-sized planetesimals, to the embryo themselves. The reason for this intense research activity is that this stage is potentially the one that is most affected by binary perturbations. Indeed, in the standard planet-formation version, this stage proceeds through fast runaway and oligarchic growth that require very low impact velocities between colliding bodies, typically smaller than their escape velocity, i.e., just a few m.s^{-1} for kilometer-sized objects (e.g., Lissauer, 1993). It is thus very sensitive to dynamical perturbations, the crucial parameter sealing the fate of the planetesimal population being the distribution of *encounter velocities* dv among them. As this field of research is a (very) fast evolving one, let us here briefly summarize and synthesize the main results obtained so far, especially in the past couple of years.

Early works (e.g. Heppenheimer, 1978) revealed that estimating the dv distribution is not straightforward. In the complex dynamical environment of a binary, dv is indeed no longer directly proportional to the bodies eccentricity e and inclination i , because planetesimal orbits are strongly phased and not randomly distributed in periastron and ascending nodes.

The pioneering study of Marzari & Scholl (2000) later showed that a fundamental mechanism controlling planetesimal dynamical evolution is the coupling between secular perturbations forced by the companion and friction with the primordial gas that is left in the protoplanetary disc at this stage. This coupling results in a strong phasing of planetesimal orbits. Thébault et al. (2004, 2006) have shown that this phasing is size-dependent, so that $d\nu$ are small between equal-sized objects but can reach very high values for bodies of different sizes. For most "reasonable" size distributions within the planetesimal population, the differential phasing effect is the dominant one (Thébault et al., 2006). This can lead to an accretion-hostile environment in vast regions of the circumprimary disc, which can stretch much closer to the primary than the radial limit for orbital stability or embryo accretion. Furthermore, even in most of the regions where planetesimal accretion *is* possible, it cannot proceed in the same way as around a single star, because the $d\nu$ increase is still enough to strongly slow down and impede the runaway growth mode. A worrying result was that, for the emblematic γ Cephei case, the location at which the planet is observed is probably too perturbed to allow for the planetesimal accretion stage to proceed (Paardekooper et al., 2008). Similarly troublesome results were later obtained for potential planets in the habitable zone (HZ) of both stars of arguably the most famous binary system: α Centauri (Thébault et al., 2008, 2009).

These pessimistic studies were all considering a simplified static and axisymmetric gas disc. However, the simulations of Paardekooper et al. (2008) showed that the situation gets even worse when considering a dynamically evolving gas disc: gas streamlines and planetesimals follow very different orbits, which in most cases increases gas friction and thus the accretion-hostile effect of differential phasing of planetesimals. On a more positive note, Xie & Zhou (2009) and Xie et al. (2010a) showed that a small inclination of a few degrees between the circumprimary gas disc and the binary orbital plane could in fact help accretion. This is because planetesimal orbital inclinations are segregated by size, thus favouring low- $d\nu$ impacts between equal-sized bodies over high- $d\nu$ impacts between differently-sized objects. As a result, planetesimal accretion could become possible, albeit in a very slowed down form, in the HZ of α Cen. However, a very recent study by Fagner et al. (2011) seems to indicate that taking into account the effect of the gas disc's gravity could offset this positive effect of orbital inclination, leading to high $d\nu$ dynamical environments.

This planetesimal accretion issue is thus far from having been solved, and is in any case very dependent of the set up: binary orbit, relative masses of the star, location in the circumprimary disc, etc. (Thébault et al., 2006).

1.4 HD196885

Given the huge parameter space to explore, most studies of planet formation in binaries consider only one specific and illustrative example. It is usually either α Centauri, because of its obvious interest as our closest neighbour and potential for planet detection (Guedes et al., 2008), or γ Cephei, because it was until recently the most "extreme" exoplanet in a binary, in the sense that it is the one, given its large distance

to the primary and proximity to the secondary, for which companion perturbations are expected to be the strongest.

This "privileged" position of γ Ceph has however been challenged by a recent study by Chauvin et al. (2011) on HD196885. This system had already been identified as a planet-hosting binary (Chauvin et al., 2007), but only the companion's projected distance was known, not the binary's orbit. With new observations, Chauvin et al. (2011) were able to constrain this orbit to $a_B = 21.0 \pm 0.86$ AU and $e_B = 0.42 \pm 0.03$, and refined the exoplanet orbit to $a_P = 2.6 \pm 0.1$ and $e_P = 0.48 \pm 0.02$ (a value close to the earlier estimate by Correia et al., 2008). This makes HD196885Ab a more extreme binary exoplanet than γ Cephei Ab. One way to quantify it is by looking at the Holman & Wiegert (1999) criteria for orbital stability, which gives a critical radial distance (to the primary) of $a_{crit} = 3.71$ AU for γ Ceph and 3.82 AU for HD196885, thus placing the planet at ~ 1.7 AU from the orbital stability limit in γ Ceph but at only ~ 1.2 AU for HD196885. In fact, this planet's eccentricity, $e_P = 0.48$, makes it reach ~ 3.85 AU, i.e. slightly *beyond* a_{crit} , although this does not necessarily mean its orbit is unstable, since a_{crit} is not a razor sharp boundary (the formula of Holman & Wiegert (1999) comes with error bars delimiting a "gray" area around a_{crit}). However, a preliminary numerical analysis by Chauvin et al. (2011) indicates that this planet might possibly be on an unstable orbit, unless there is a high (unconstrained) inclination between the binary plane and the planet orbit. These stability issues need to be further investigated, but it is clear that this system is by far the most "extreme" planet-in-a-binary so far.

1.5 present work

We shall not reinvestigate the issue of the planet's long-term stability, nor shall we investigate the possible cause for its high eccentricity of 0.48. We shall here focus on the key issue of the *formation* of a planet in such a perturbed environment. HD196885Ab is indeed clearly the planet that poses the strongest challenge to any planet-formation model, especially regarding the planetesimal-accretion stage. We numerically investigate under which conditions this stage might, or might not, proceed in HD196885A's circumprimary disc. As with most previous similar studies, we follow the distribution of one crucial parameter: impact velocities amongst planetesimals. Our aim is to identify the regions where the dynamical environment is too perturbed to allow classical core-accretion of a planet. To obtain conservative results, we shall consider the most favourable (i.e., accretion friendly) assumptions for our simulation: axisymmetric static gas disc, no self gravity. We present our numerical model in Sec.2. Our main results are presented in Sec.3. In Sec.4, we discuss the robustness of our main conclusions, i.e., that most of the circumprimary disc is hostile to accretion, and consider several possible solutions to the apparent paradox of having a planet in a accretion-hostile region. Conclusions are presented in Sec.5.

2 Model

We follow a population of $N = 2 \times 10^4$ planetesimals, sampling a much larger population of "real" physical planetesimals, orbiting the primary and dynamically perturbed by the companion. The forces acting on the particles are both stars' gravity and friction with the primordial gas disc. The code has a built-in collision search algorithm, tracking, at each time step, all mutual encounters between all bodies. In order to yield a statistically significant number of encounters despite the limited number of particles as compared to a real planetesimal population, we resort to the usual method of assigning an inflated radius to each particle (e.g. Thébault & Brahic, 1998; Marzari & Scholl, 2000; Charnoz et al., 2001; Lithwick & Chiang, 2007; Xie & Zhou, 2008). For a more detailed description of our algorithm, see for example Thébault & Brahic (1998) and Thébault et al. (2006).

Gas drag is computed following Weidenschilling & Davis (1985):

$$\mathbf{F} = -K v_{p-g} \mathbf{v}_{p-g}, \quad (1)$$

where \mathbf{F} is the force per unit mass, \mathbf{v}_{p-g} the velocity of the planetesimal with respect to the gas, v_{p-g} the velocity modulus, and K is the drag parameter given by:

$$K = \frac{3\rho_g C_d}{8\rho_{pl}s}, \quad (2)$$

where ρ_g is the gas density, and ρ_{pl} and s are the planetesimal density and radius, respectively. The coefficient C_d is a dimensionless quantity related to the shape and size of the body (≈ 0.4 for spherical bodies). The gas disc is assumed to be static and axisymmetric. For the gas density and gas velocity, we follow Takeuchi & Lin (2002) and assume

$$\rho_g(r, z) = \rho_{g0} \left(\frac{r}{AU} \right)^p \exp \left(-\frac{z^2}{2h_g^2} \right), \quad (3)$$

and

$$v_g(r, z) = v_{k, \text{mid}} \left[1 + \frac{1}{2} \left(\frac{h_g}{r} \right)^2 \left(p + q + \frac{q}{2} \frac{z^2}{h_g^2} \right) \right] \quad (4)$$

where $h_g(r) = h_0(r/AU)^{(q+3)/2}$ is the scale height of the gas disc and $v_{k, \text{mid}}$ is the Keplerian velocity in the midplane. We consider the Minimum Mass of Solar Nebula (MMSN, see Hayashi, 1981) as a reference disc, where $p = -2.75$, $q = -0.5$, $\rho_{g0} = 1.4 \times 10^{-9} \text{ g.cm}^{-3}$, and $h_0 = 4.7 \times 10^{-2} \text{ AU}$.

The static and axisymmetric assumption are taken for computing time reasons but is of course a crude simplification of the real behaviour of a circumprimary gas disc, which should react to the companion's perturbations and display pronounced eccentric shapes and azimuthal anisotropies (e.g. Artymowicz & Lubow, 1994). However, preliminary studies with evolving gas discs (Paardekooper et al., 2008) have shown that gaseous friction, and in particular the differential phasing effect according to planetesimal size, is higher than for a static gas disc. This is because the gas disc gets eccentric (Goodchild & Ogilvie, 2006), with an eccentricity e_g and a precession rate that in most cases strongly departs from that of the planetesimals (see for instance

Table 1 Setup for the nominal run (see main text for parameter definition)

Binary mass ratio	$\mu = 0.35$
semi-major axis	$a_b = 21.0$
eccentricity	$e_b = 0.42$
Number of test particles	2×10^4
Inflated radius (collision search routine)	5×10^{-5} AU
Physical radius	$1 \text{ km} \leq s \leq 10 \text{ km}$
Initial semi-major axis	$0.9 \text{ AU} \leq a \leq 3.1 \text{ AU}$
Initial eccentricity	$0 \leq e \leq 5 \times 10^{-5}$
Initial inclination	$0 \leq i \leq 2.5 \times 10^{-5}$
Gas Disc density at 1AU	$\rho_0 = 1.4 \times 10^{-9} \text{ g.cm}^{-3}$
radial profile	$\rho_g(r) \propto r^{-2.75}$
scale height	$h_g = 4.7 \times 10^{-2} (r/1\text{AU})^{1.25} \text{ AU}$
vertical profile	$\rho_g(z) \propto \exp(-z^2/2h_g)$

a clear illustration in Figs.9 and 10 of Paardekooper et al., 2008). This increases the relative velocities between planetesimals and gas streamlines, and thus the friction of the latter on the former. This makes the systems globally more accretion hostile than in the axisymmetric case (see Sec.1.3). As a consequence, the axisymmetric assumption should be regarded as a limiting best-case scenario for planetesimal accretion.

2.1 setup

We consider a disc of planetesimals with initial semi-major axis $0.9 \leq a \leq 3.1$ AU, having randomly distributed orbits (longitude of periastron and of ascending node) and initial eccentricity $0 \leq e \leq 5 \times 10^{-5}$ and inclination $0 \leq i \leq 2.5 \times 10^{-5}$. This ensures that initial encounter velocities are such as $dv_{init} \sim 1 - 2 \text{ m.s.}^{-1}$, approximately the escape velocity of a 1km body. This is the velocity distribution expected in an unperturbed population of km-sized planetesimals, in which runaway growth can proceed (Lissauer, 1993). The planetesimals physical sizes are randomly distributed between 1 and 10 km. The inflated radius for the collisional search routine is 5×10^{-5} AU. This size is large enough to yield a statistically significant number of impacts, but small enough not to introduce any bias in estimating dv . The set-up for our nominal run is summarized in Tab.1.

2.2 Accretion and Fragmentation Prescription

Our simulations provide us with the distribution of encounter velocities $dv_{(s1,s2)}$ for all impacting planetesimal pairs of sizes s_1 and s_2 . A key issue is then to interpret these velocities and see if they are low enough to allow accretion or are on the contrary too high and lead to mass loss or fragmentation of the impactors. Three different regimes are possible, defined by two critical velocities $v_{esc(s1,s2)}$ and $v_{ero(s1,s2)}$:

- $dv_{(s1,s2)} \leq v_{esc(s1,s2)}$: "Unperturbed" case. The impact velocity is only marginally increased with respect to its initial $dv_{init} \sim 1 - 2 \text{ m.s.}^{-1}$ value and stays below the escape velocity $v_{esc(s1,s2)}$ for the impacting pair. In this case, "normal", single-star like runaway accretion is possible.

- $v_{esc(s1,s2)} \leq dv_{(s1,s2)} \leq dv_{ero(s1,s2)}$: "Perturbed accretion" case. The impact velocity is increased beyond the escape velocity. This switches off the runaway growth mode. However, dv stays at a value small enough to allow some accretion between the impacting bodies.
- $v_{ero(s1,s2)} \leq dv_{(s1,s2)}$: "Erosion". In this case velocities are too high to allow accretion. Each impacts results in mass loss, i.e., erosion or fragmentation of one or both impactors.

While the value of $v_{esc(s1,s2)}$ is easy to derive, the erosion threshold velocity $v_{ero(s1,s2)}$ is much more difficult to estimate, as it depends on many physical parameters (particle sizes, composition, impact velocity and angle, etc...) and because, even for the same set of parameters, there exists many diverging estimates of the accretion/erosion limit (see the discussion in Thébault & Augereau, 2007). In previous papers (Thébault et al., 2006, 2008, 2009) we considered a complex, and rather cumbersome prescription for $v_{ero(s1,s2)}$, trying to connect several possible impact regimes (cratering, shattering) and to synthesize several available estimates from the literature. In the meantime, a remarkable study by Stewart & Leinhardt (2009) has been published, presenting an innovative and simplified criteria for the disruption of planetesimals. Even if this study's title claims that it is only valid for the "catastrophic" disruption of planetesimals, it is in fact applicable to a larger domain, including impacts usually described as non-catastrophic (where the biggest remaining fragment is more than half the mass of the impactor). Although the results of Stewart & Leinhardt (2009) have their limitations, we follow Fagnier et al. (2011) and adopt their prescription here because of its simplicity and its self-consistency. Its main parameter is the velocity-dependent "reduced" catastrophic disruption specific energy

$$Q_{RD}^* = q_S s_c^{9\alpha/(3-2\Phi)} dv^{2-3\alpha} + q_g s_c^{3\alpha} dv^{2-3\alpha} \quad (5)$$

where $s_c = (s_1^3 + s_2^3)^{1/3}$ is the reduced radius of the combined projectile and target mass, and α and Φ are material properties. If $Q_R = 0.5m_1m_2dv/(m_1 + m_2)^2$ is the reduced kinetic energy, then the mass m_{lr} of the largest remaining fragment is given by

$$\frac{m_{lr}}{(m_1 + m_2)} = 1 - 0.5 \frac{Q_R}{Q_{RD}^*} \quad (6)$$

With the convention that $m_1 \geq m_2$, the criteria for accretion is then $m_{lr} \geq m_1$, which translates into

$$dv \leq v_{ero(s1,s2)} = \left[4 \left(1 + \frac{m_2}{m_1} \right) Q_{RD}^* \right]^{0.5} \quad (7)$$

We follow Stewart & Leinhardt (2009) and consider two limiting cases: v_{ero1} for weak rocky aggregates ($\alpha = 0.4$, $\Phi = 7$, $q_S = 500$, $q_g = 10^{-4}$, in cgs units) and v_{ero2} for strong compact rocks ($\alpha = 0.5$, $\Phi = 8$, $q_S = 7 \times 10^{-4}$, $q_g = 10^{-4}$).

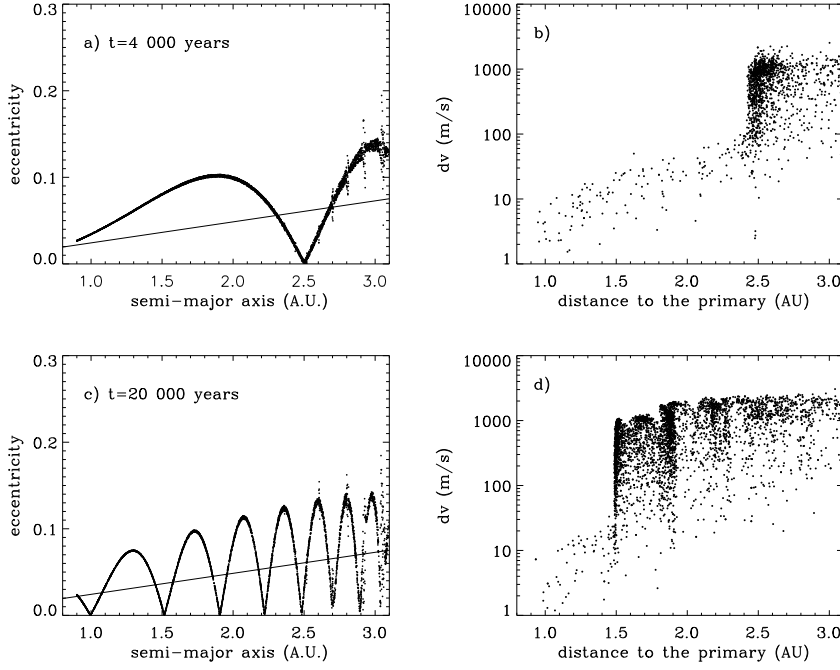


Fig. 1 Gas free case. Snapshots, after $t = 4 \times 10^3$ and $t = 2 \times 10^4$ years, of the eccentricity distribution (left-hand side) and encounter velocity distribution (right-hand side) within the planetesimal population, as a function of semi-major axis (for the eccentricity) and radial distance to the primary (dv panels). The straight line on the (e,a) panels indicates the value of the forced secular eccentricity e_f . The velocity distribution is obtained by recording all impacts in the $t \pm 100$ years time interval. The inward propagation of the high- dv "wave", due to orbital crossing of neighbouring orbits, is clearly visible.

3 Results

3.1 Gas Free Case

In order to clearly identify the different mechanisms at play, we first present a fiducial and pedagogical run with no gas. Note that planetesimal physical sizes are irrelevant for this purely gravitational case. Figs. 1a and c show the classical build up of large secular eccentricity oscillations around the forced eccentricity e_f . These oscillations are due to the fact that, at each radial distance from the primary, eccentricities vary with time following a sinusoidal function

$$e(a, t) = 2 e_f \left| \sin(ut/2) \right| = \frac{5}{2} \frac{a}{a_b} \frac{e_b}{1 - e_b^2} \left| \sin(ut/2) \right| \quad (8)$$

whose frequency u vary with semi-major axis (e.g. Thébault et al., 2006). As has been pointed out in previous studies, such oscillations do not immediately lead to high impact velocities, because neighbouring orbits are strongly phased. However, because the a dependency of particle eccentricities increases with time (since u depends on a),

the $e(a)$ -oscillations get narrower with time and orbits within one oscillation "wave" eventually cross, at which point very high dv are suddenly reached (see discussion in Thébault et al., 2006). The radial location at which orbits cross moves inward with time following the empirical law derived by Thébault et al. (2006):

$$a_{cross} \sim 0.37 \frac{(1 - e_b^2)^{1.07}}{e_b^{0.36}} \left(\frac{M_b}{1M_\odot} \right)^{-0.39} \left(\frac{a_b}{10\text{AU}} \right)^{1.53} \left(\frac{t}{10^4\text{yr}} \right)^{-0.36} \text{AU}. \quad (9)$$

Note that the location and timing of the orbital crossing does only weakly depend on the initial conditions for planetesimal orbits. We have chosen here the simplest and probably less unlikely case of initial circular orbits (for more on this issue, see the discussion in Thébault et al., 2006), but taking initial eccentric orbits will roughly lead to the same behaviour for a_{cross} , the only change being an additional free component to the encounter velocities.

From Fig.1b, we see that a_{cross} , i.e. the location beyond which there is an abrupt increase of impact velocities, reaches 2.6 AU (the present location of the planet) in less than 4×10^3 years. At this point, encounter velocities increase by more than a factor ~ 20 . However, even the short timespan before orbital crossing is not fully calm, because of sporadic high- dv impacts (100 to 200m.s^{-1}) with particles in the nearby mean motion resonances clearly seen on Fig.1a. In this gas-free case, the $r \sim 2.6$ AU region is thus very hostile to low- dv planetesimal accretion.

The situation is less desperate closer to the primary. The regions inside 1.5 AU is for instance protected from orbital crossing, and high- dv , for more than 2×10^4 years (Fig.1d). This should in principle leave enough time for runaway accretion to produce embryos from kilometre-sized planetesimals. However, we shall see that gas drag completely obliterates these optimistic conclusions.

3.2 Nominal Run with Gas

Gas drag radically changes the dynamical evolution of the system. Its main effect is to phase both planetesimal eccentricities (Fig.2a and c) and longitude of periastron ω (Fig.2b and d) according to their size s . As shown in Fig.2c, the initially large eccentricity oscillations are progressively damped. The system will eventually tend towards a steady state, where all eccentricities reach an equilibrium value $e_{(a,s)}$ depending on semi-major axis and size. In the innermost regions with higher gas densities, this steady state is reached relatively quickly for all particles in our 1-10 km size range. Beyond ~ 1.4 AU, however, the steady state has not been reached, at $t = 2 \times 10^4$ years, for the biggest planetesimals. And at the location of the planet, 2.6 AU, even the smallest 1 km objects still have residual eccentricity variations at the end of the run (Fig.2c).

These dynamical behaviours have clear consequences on impact velocities, which reach high values everywhere in the disc (Fig.3). These high dv are reached very quickly, a few 1000 years, and this for two different reasons depending on location within the disc:

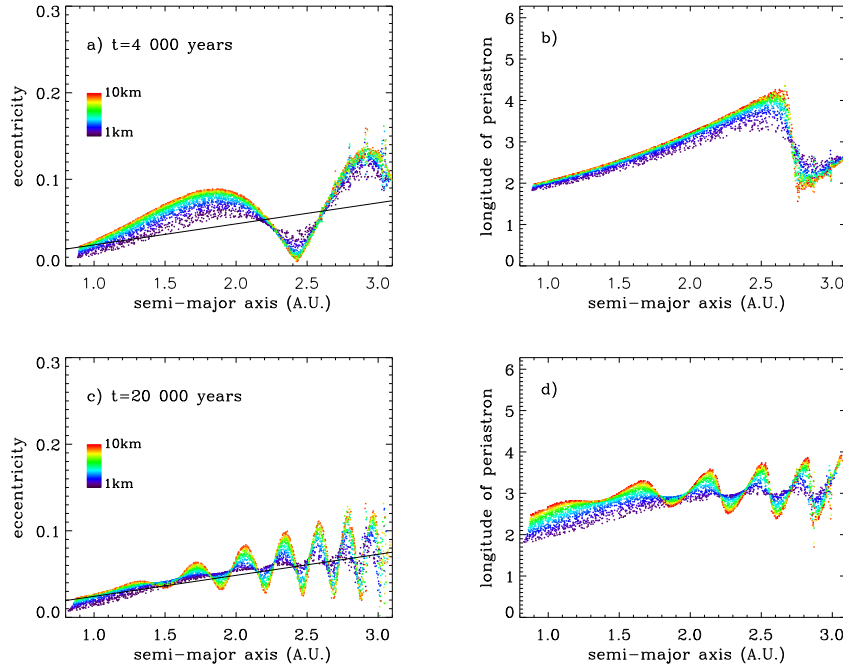


Fig. 2 Nominal case with gas friction from a 1xMMSN disc: eccentricity (left panels) and longitude of periastron (right panels) as a function of semi-major axis (the binary’s longitude of periastron is 0), at $t = 4 \times 10^3$ and $t = 2 \times 10^4$ years, for a population of planetesimals in the $1 \leq s \leq 10$ km size range.

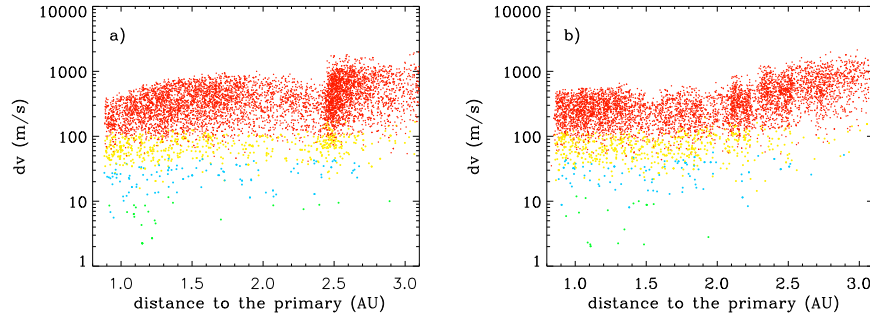


Fig. 3 Same nominal gas-friction run as in Fig.2: impact velocity distribution as a function of radial distance to the primary. The colours indicate the expected collision-outcome regime for each impact: “unperturbed” runaway accretion (*green*), perturbed accretion (*blue*), erosion (*red*). The yellow area is for impacts where $v_{ero1} \leq dv \leq v_{ero2}$, for which the collisional outcome is uncertain (see text for details).

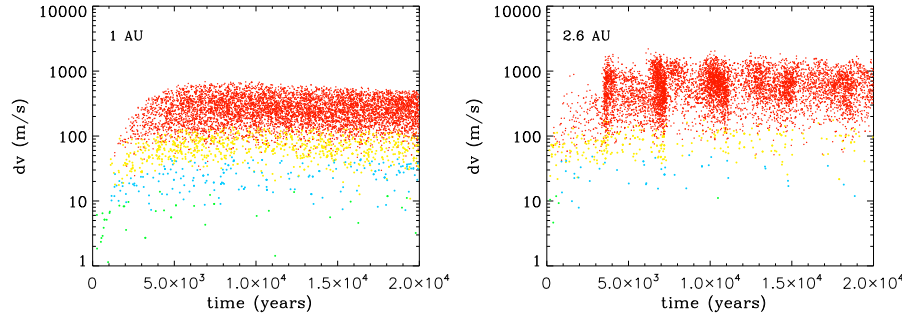


Fig. 4 Nominal gas drag case. Time evolution of the impact velocity distribution at 2 different locations in the disc. All impacts are recorded in a narrow ring of width 0.02 AU around the central location. The colour scale is the same as in Fig.3.

- In the inner disc, shortwards of $\sim 2\text{--}2.5$ AU, where gas densities are high, the differential phasing induced by gas drag, and the velocity increase that comes with it, is felt very early on, long before orbits reach a steady state with fixed e and ω . This is illustrated in Fig.3a showing that, at $t = 4 \times 10^3$ years, when no region of the disc has reached a steady state yet, dv already reach values $\geq 300 \text{ m.s}^{-1}$ in the whole ≤ 2.5 AU region.
- In the $r \geq 2.5$ AU region, the gas drag-induced dv increase is weaker, but velocities nevertheless reach even higher values, $\sim 1000 \text{ m.s}^{-1}$, because of the purely dynamical orbital crossing effect identified in the gas-free runs. This is clearly illustrated by the dv "jump" at ~ 2.5 AU in Fig.3a.

. The velocity distribution at $t = 2 \times 10^4$ years is remarkably similar to the one at 4×10^3 years. The only difference is in the outermost regions, where no dv jump is longer visible, because gas drag is now the dominant dv -inducing mechanism in the whole system¹ (even if a steady state has *not* been reached in these outer regions). To illustrate these behaviours more clearly, we display in Fig.4 the temporal evolution of dv in two opposite regions of the disc. At 1 AU, differential phasing induces a high- dv regime after $\sim 2 \times 10^3$ years, while a steady state is reached after $\sim 5 \times 10^3$ years. At 2.6 AU (the planet location), three successive phases can be distinguished: a first phase, starting after only a few 100 years, of moderate-to-high- dv induced by sporadic impacts with objects in neighbouring resonances, followed by a second stage, at $t = 4 \times 10^3$ years, when orbital crossing occurs and increases dv to even higher values, and finally a third stage, starting around 1.5×10^3 years, when gas drag phasing progressively takes over as the dominant dv -inducing mechanism. Despite these differences, however, the important result is that a high- dv regime, regardless of its different causes depending on location in the disc, is reached after only a few 1000 years in both the inner and outer regions of the disc.

To estimate the global consequences of this high- dv regime on the accretional evolution of a "real" population of planetesimals, one has to consider a parameter

¹ This $t \sim 2 \times 10^4$ years time is thus the characteristic timescale for gas drag to dominate the whole system's dynamics

that has been ignored so far: the planetesimal *size distribution*. In our simulations, a flat distribution between 1 and 10 km has been considered for the sake of simplicity, but real distributions should be more complex. This issue of the initial planetesimal size distribution is a difficult one. In models of planetesimal accretion in our solar system, a single "initial" planetesimal size is usually assumed (Makino et al., 1998; Kokubo & Ida, 2000), but this assumption is taken for the sake of simplicity and there should be some size dispersion in any realistic initial planetesimal population. The exact profile of this initial distribution is difficult to constrain. Firstly because it depends on the way planetesimals are formed from smaller grains and pebbles, a process which is still far from being fully understood, even if significant progresses have been made in recent years (Johansen et al., 2007; Cuzzi et al., 2008). Furthermore, the very concept of an "initial" size distribution can be questioned, as there might be a wide spread in the times at which km-sized objects appear in a given region of the disc (Chambers, 2010; Xie et al., 2010b). These issues go well beyond the scope of the present paper, and we shall consider, following Thébault et al. (2008, 2009) and Xie & Zhou (2009), a Maxwellian distribution centered on $s = 5$ km. Such a relatively peaked distribution is, in line with our conservative approach, a priori more accretion-friendly since it minimizes the rate of encounters between differently-sized objects. It also agrees with most planetesimal-formation scenarios' conclusion that there should be a privileged size for initial planetesimals. In practice, we weight each s_1-s_2 impact obtained in our run with a flat size distribution by a factor $f_{(s_1,s_2)}$ accounting for the Maxwellian distribution².

The accretion/erosion behaviour of the whole disc is displayed, at $t = 10^4$ years, in Fig.5. As can be clearly seen, the rate of impacts leading to mass erosion or fragmentation is $\geq 80\%$ everywhere, except around 1.6 AU where it is $\sim 65\%$. When discarding the impacts with "uncertain" (yellow) outcome, the level of accreting impacts is less than 10% everywhere. Moreover, among these accreting impacts, most of them are in the "perturbed" mode (blue), with almost no impact allowing runaway growth (green). We have tried different size-distributions and always found the same global accretion-hostile trend, except for extremely peaked, and probably unrealistic, distributions. Only with much larger planetesimals can this negative trend be reversed (see Sec.3.4).

3.3 Inclined Binary

Xie & Zhou (2009) have shown that a small inclination between the binary and the circumprimary disc can help accretion by segregating particle inclinations according to sizes, thus favouring impacts between equal-sized bodies. We explored this possibility for the present HD196885 case, assuming a small inclination of 2° for the binary. As shown in Fig.6, an improvement is obtained compared to the coplanar case (Fig.5). Accreting impacts now make up between 5 and 20% of all impacts in most of the disc. However, the system is still globally hostile to accretion everywhere (between 60 and 80% of "red" impacts), especially at the location of the planet (2.6 AU)

² The reason why we do not run a simulation with a Maxwellian distribution to start with is because, with a flat 1-10km distribution, we can get a good statistics on all possible impacting sizes $s_1 - s_2$

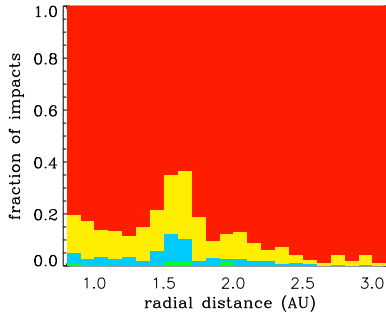


Fig. 5 Nominal gas drag case. Relative importances, at $t = 10^4$ years, of the 4 possible collision outcomes as a function of radial distance to the primary (the colour scale is the same as in Figs.3 and in Fig.4). A Maxwellian size distribution centered on 5 km is assumed.

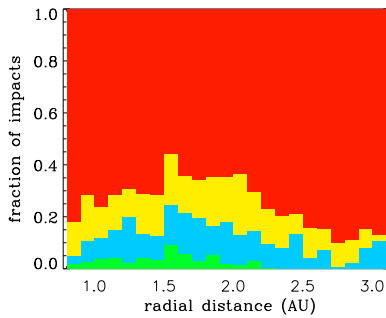


Fig. 6 Same as Fig.5, but with a binary inclined by 2° with respect to the circumprimary disc.

where the fraction of eroding impacts is in excess of 90%. We have tried several different values for the binary inclination in the $1^\circ \leq i \leq 10^\circ$ range, and always end up with results very similar to those displayed in Fig.6, i.e., a system that is globally very hostile to accretion.

Strengthening our conclusions is also the fact that the vertical segregation according to particle sizes obtained by Xie & Zhou (2009) is probably unrealistically high. This is because it has been obtained for an axisymmetric gas disc, whereas a real gas disc would get eccentric and tend to diminish the size-sorting effect. Our results for an inclined binary, also obtained with an axisymmetric gas disc, should thus be considered as a best-case scenario regarding planetesimal accretion; a best-case scenario for which no accretion is possible in the whole ≥ 0.9 AU region.

3.4 Large planetesimals

As suggested by Thébault et al. (2008) and, using slightly different assumptions, by Beauge et al. (2010), another possible solution to the accretion-hostile-velocities dilemma

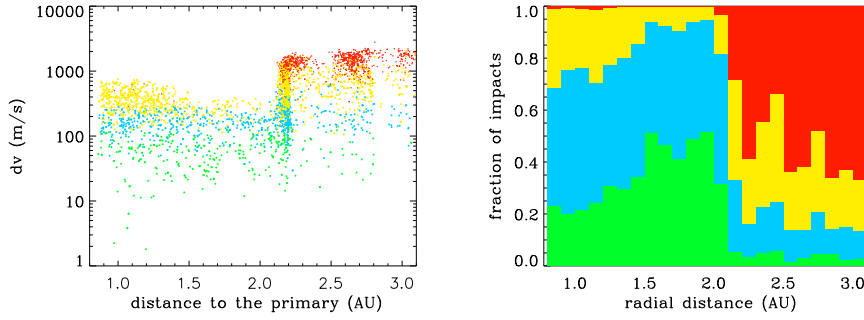


Fig. 7 Large planetesimals ($10 \leq s \leq 100$ km) case. Encounter velocity distribution at $t = 10^4$ years (left) and respective balance between collision outcomes (right). The colour scale is the same as in Fig. 5.

is to start from larger planetesimals. We explore this hypothesis by considering a population of initial planetesimals in the 10-100 km range. Taking larger objects reduces the impact of gas drag and its subsequent effect on increasing dv among planetesimals. This is what is observed in the inner regions of the disc in Fig. 7a, where impact velocities are lower than for the 1-10 km population (Fig. 3a). This situation is more favourable for accretion, a tendency that is amplified by the fact that, for a given dv , bigger planetesimals are more resistant to impacts than smaller ones (in the gravity regime valid for objects in the ≥ 1 -10 km range). As a result, at $t \sim 10^4$ years, the whole region shortwards of ~ 2 AU is accretion-friendly for 100 km planetesimals (Fig. 7b). In the outer regions, however, the situation is radically different: the values of dv are much higher because of the secular orbital crossing effect. In these outer gas-poor regions, large planetesimals behave almost as test particles in the gas-free case. In regions of orbital crossing, impact velocities are high enough to lead to erosion even for 100 km objects (Fig. 7b). As in the gas-free case, the high- dv orbital crossing "front" reaches 2 AU in $\sim 10^4$ years, but the 2.6 AU location is reached in less than 4×10^3 years.

4 Discussion

The previous results all tend to indicate that the HD196885 circumprimary disc is strongly hostile to the accretion of kilometre-sized bodies. This is especially true of the region at 2.6 AU from the primary, i.e., around the current location of the detected planet. Planetesimals are basically caught between a rock and a hard place: in the inner regions secular perturbations combined to gas drag induce high- dv between all non-equally-sized objects, while in the outer regions high- dv are due to secular perturbations *alone*, which make orbits cross within a few thousand years.

4.1 Limitations, robustness of our conclusions

As underlined earlier, our numerical exploration relies on several simplifications. It has also many free parameters that cannot be all thoroughly explored. How robust are our conclusions, especially regarding the 2.6 AU region, with respect to these limitations?

Timescale. We first note that timescale is not a critical issue: high- dv are reached almost everywhere after only a few 10^3 years. The only change with time is that gas drag progressively takes over as the dominant dv -inducing process even in the outer regions.

Binary inclination. As shown by Xie & Zhou (2009), a small inclination between circumprimary disc and binary orbital plane acts in favour of planetesimal accretion. This point is all the more appealing because this inclination is in most cases an unconstrained parameter, even for close binaries, for which the assumed "coplanarity" is not constrained to less than $i_b \sim 10^\circ$ (Hale, 1994). In the present case, however, even if the situation improves significantly for i_b of a few degrees, it is far from enough to reverse the general accretion-hostile trend of the system (Fig.6). In addition, as pointed out in Sec.3.3, the vertical size-sorting of planetesimals, and its effect in favour of accretion, is probably overestimated in a circular gas-disc case. As a consequence, we believe our conclusions of an accretion-hostile disc with a slightly inclined binary to be relatively robust.

Of course, even higher values of i_b could be possible, as might be suggested by the preliminary long-term stability study of Chauvin et al. (2011). These high inclination cases cannot be explored with the present model, and will be the purpose of a forthcoming general study devoted to this issue (Xie et al., submitted), but it seems very unlikely that impact velocities should be reduced in such high- i_b systems, especially when the Kozai regime sets in.

Gas disc profile. We have run several additional simulations (not shown here), exploring different gas disc profiles and densities. In almost all cases, results are roughly comparable to the nominal case: high, and accretion-inhibiting impact velocities in the whole $r \geq 0.9$ AU region. Only for very tenuous discs do we get an accretion-friendly inner region for more than 10^4 years, which is basically the gas-free result displayed in Fig.1. It could be argued that this gas-free stage is the one towards which the real circumprimary disc is naturally evolving, since primordial gas is expected to be removed after a few 10^6 years in protoplanetary discs, or even less than that for close binaries (Cieza et al., 2009). In fact, Xie & Zhou (2008) have shown that some orbital rephasing could occur during the gas removal phase, possibly rending the disc accretion-friendly again. However, as shown by Thébault et al. (2008), it is unlikely that planetesimals could survive the long accretion-hostile period *before* gas removal without being grounded to dust and removed by gas friction. The only solution would be that planetesimals form late in the disc's history, when few or not gas is left, but this hypothesis conflicts with all planetesimal formation models. In any case, let us

stress that even in this unlikely scenario, the region around 2.6 AU would still be hostile to planetesimal accretion, due to secular effects *alone*.

There is however another important gas-disc-related issue to consider here, i.e., that all our runs follow the same crude simplification, inherent to our approach, of a static axisymmetric gas disc. Nevertheless, as discussed in Sec.2, we expect planetesimals imbedded in evolving gas discs to have impact velocities that are even higher than in the fiducial static case (Paardekooper et al., 2008). So here again, our dv estimates do give a conservative lower estimate.

Gas self gravity. Another simplification of our model, as well as of most previous studies of planetesimals in binaries, is the neglect of the gas disc's gravity. To our knowledge, the only published studies taking into account disc gravity are Kley & Nelson (2007) and the very recent work by Fragner et al. (2011). These pioneering studies present results with a limited number of particles (which is the price to pay for including the disc's gravity) that does not allow accurate dv estimates, and for which it is difficult to untangle the effect of gravity from that of gas drag. However, it appears clearly that the global qualitative effect of disc gravity is to further *increase* impact velocities, by adding an additional jitter to the eccentricity and periastron evolution of planetesimal orbits³. We do thus expect our gas drag-only simulations to here again give a lower limit for "real" impact velocities.

4.2 A planet in an accretion-hostile environment?

That most of the circumprimary disc is too excited to allow planetesimal accretion seems to be a relatively robust result for the HD196885 system. And yet there *is* a planet well inside this accretion-hostile region. There are basically four potential solutions to this paradox: either 1) the planet could form in situ by being able to bypass the mutual-planetesimal-accretion phase, or 2) it was formed elsewhere and was later injected at its present location, or 3) the binary had a different orbit during its early history, or 4) the planet did not form by core-accretion but by direct disc instability.

4.2.1 Bypassing the kilometre-sized planetesimals accretion phase?

The most obvious potential way to bypass this stage is if planetesimals were formed big, i.e., not in the kilometre-sized range but rather in the 50-100 km one. Interestingly enough, this big-initial-planetesimals scenario seems to be the one favoured by the most recent planetesimal-formation models of Johansen et al. (2007) and Cuzzi et al. (2008). Moreover, according to Morbidelli et al. (2009), there seems to be observational evidence for an initial population of large, ≥ 100 km, bodies in the asteroid belt, even if this conclusion has been recently questioned, for different reasons, by Minton & Malhotra (2010) or Xie et al. (2010b). For the present problem, however, there are some issues with this large-planetesimals hypothesis. The first one is that, to

³ This is also the preliminary conclusion of Marzari et al. (2008), who also investigated disc gravity, but in the different context of a *circumbinary* disc.

our knowledge, there has been no study of how these big-planetesimal formation scenarios, for which several problems remain to be solved even for a normal single-star environment, could proceed in the highly perturbed environment of a close binary. The second, and more problematic issue for the specific HD196885 case is that, even *if* initial planetesimals are ~ 100 km big, the region around 2.6 AU is still hostile to accretion (see the "large planetesimals" run in Fig.7). We ran an additional test simulations and found that the 2.6 AU region becomes accretion-friendly only for bodies with sizes ≥ 250 km. It is far from being assured that planetesimals can be born this big, especially in a highly perturbed close binary.

Another possibility to overcome the mutual-planetesimal-accretion hinder, even in the case of small planetesimals, is the so-called "snowball" growth mode first encountered in the simulations of Paardekooper & Leinhardt (2010) and investigated in more detail by Xie et al. (2010b). In this scenario, planetesimals grow preferentially by sweeping up of small dust particles, provided that the local mass density of solids contained in dust, $\rho_{S(dust)}$, exceeds that contained in planetesimals, $\rho_{S(plan.)}$. The snowball growth mode is especially appealing for dynamically excited systems such as close binaries because the accretion of dust onto planetesimals should tolerate much higher velocities than the mutual accretion of the planetesimals themselves. Exactly how much higher is not clear yet, as there exists to our knowledge no published study of the velocity dependence of the accretion efficiency of dust on large targets, at least for the $dv \geq 500 \text{ m.s}^{-1}$ regime encountered here ⁴. One additional issue is of course whether or not the $\rho_{S(dust)} \geq \rho_{S(plan.)}$ criteria is met in real systems. As shown by Xie et al. (2010b), this condition could be fulfilled if there is a significant spread in the times at which planetesimals do appear in the system, as would for instance be expected for the Cuzzi et al. (2008) scenario. But even if that is not the case, the $\rho_{S(dust)} \geq \rho_{S(plan.)}$ condition could be met later on in a perturbed system's evolution, when the quantity of dust produced by destructive planetesimal-on-planetesimal impacts exceeds the mass left in the remaining unshattered planetesimals (Paardekooper & Leinhardt, 2010). Both of these cases have so far been studied in preliminary works using simplified prescriptions: analytical expression for the growth of initially isolated planetesimals in Xie et al. (2010b), and 2-D simulations for the Paardekooper & Leinhardt (2010) studies of planetesimal re-accretion of impact-produced dust. They both will be quantitatively re-investigated in forthcoming studies (Paardekooper et al., 2011 and Xie et al., 2011, both in preparation).

4.2.2 Embryo migration, Planet-Planet Scattering?

Apart from the strongly revised versions of the planet-formation scenario presented above, there exist other potential solutions to the inhibition of the planetesimal-to-embryos stage. The first one is that embryos form in accretion-friendly regions closer to the primary and later migrate outward to the planet's present position, where they can continue to grow because the final embryo-to-planet stage is much less affected by binary perturbations (see Sec.1). This scenario has been quantitatively investigated

⁴ The "high velocities" dust impacts considered in laboratory experiments such as those of Teiser & Wurm (2009) do not exceed $50\text{-}100 \text{ m.s}^{-1}$

by Payne et al. (2009), who showed that a fraction of the embryos formed in the inner regions can indeed later move out. The relative amplitude $\delta a/a$ of this outward migration can reach 0.3 to 0.8. This is however not enough for the present case, because it means that the innermost possible origin for an embryo having moved to 2.6 AU is ~ 1.4 AU, i.e., a region that is still highly hostile to planetesimal accretion (see Fig.5).

On a related note, one could imagine that the planet fully formed in the inner, accretion friendly regions and was later ejected by gravitational interactions with a second, yet undetected, planet. There is however a major problem with this scenario, which is that the accretion-friendly region around HD196885A is very narrow. By running an additional simulation focusing on the inner $r \leq 0.9$ AU disc, we indeed find that the limit between the eroding (majority of "red" impacts) and accreting (majority of "green" + "blue" impacts) regimes is located at around 0.4 AU from the primary. This would mean that 2 giant planets⁵ would have to form within 0.4 AU from HD196885A. Such an hypothesis seems to be ruled out by all planet-formation scenarios. Another counter argument is that a second planet closer to the primary would have been detected in radial velocity measurements (Chauvin, personal communication).

4.2.3 Wider initial binary?

Another possibility is that, during these early stages of its existence, the binary's orbit was different from what it is today. This might happen because most stars are expected to be born in clusters, which are initially compact, thus allowing frequent interactions between neighbouring stars. The simulations of Malmberg et al. (2007) have shown that, for the typical cluster they considered, binaries with moderate-to-large separations do suffer early encounters that have on average shrunked their orbit. Interestingly, HD196885 is just at the limit present-day separation, ~ 20 AU, above which these orbit-shrinking effects are found to be significant (see Fig.4 of Malmberg et al., 2007). There is thus a non-negligible chance that its initial orbit, during the planet formation phase, was wider than what it is today. How much wider would it need to be in order to allow planetesimal accretion at 2.6 AU? We ran a series of test simulations with increasing values of the binary separation and found that the $r \sim 2.6$ AU region becomes accretion-friendly for $a_b \geq 45$ AU (for the same value of the eccentricity $e_b = 0.42$). This means that the binary's orbit would have had to shrink by at least 24 AU during its early history. Is such a value realistic? Unfortunately, it is impossible to judge from the Malmberg et al. (2007) simulations, since no information about the amplitude of orbital compaction was presented in this study (this important issue should clearly be investigated in future studies). However, such a large, ~ 20 -25 AU, change in semi-major axis does a priori appear unlikely for a binary that is just at the limit separation for which orbital change become significant.

⁵ the second undetected planet would also need to be massive in order to be able to perturb HD196885b

4.2.4 Formation by disc instability?

If none of the aforementioned solutions works, then a more radical alternative might be considered, i.e., to forgo the core-accretion scenario altogether. This is the conclusion recently reached by Duchêne (2010), who argued that the shorter disc lifetime in tight binaries makes it difficult to form giant gaseous planets. This study advocates a violent formation process, by direct disc fragmentation, for planets in $a_b \leq 100$ AU binaries, a hypothesis that seems to be supported by the fact that exoplanets within $a_b \leq 100$ AU binaries are significantly more massive than those within wide binaries or single stars. Such a scenario is usually invoked to explain the formation of planets at large, ≥ 100 AU semi-major axis (Boley, 2009), but Duchêne (2010) argues that, in the specific context of tight binaries, it could also work for planets much closer to their star. His main argument is that circumprimary discs in close binaries could be more compact and denser than discs around single stars ⁶, thus potentially favouring gravitational instability, and also because perturbations of the close stellar companion could give an additional trigger to instability (Boss, 2006).

However, this alternative explanation should be considered with some caution. Several studies have indeed shown that the instability scenario does also encounter major difficulties in the context of close binaries, and that no circumprimary disc gets dense enough to be unstable. As an example, Nelson (2000) or Mayer et al. (2005) conclude that instability is severely hampered by the presence of a close ($\leq 50 - 60$ AU) companion. This issue is thus far from being settled yet, and further, more detailed investigations are clearly needed to assess if disc-fragmentation can be considered as a viable alternative formation channel in close binaries.

5 Summary and Conclusions

The planet of the HD196885 system is to this day the one that has the most perturbed orbit amongst all the ~ 100 exoplanets detected within binaries. Leaving aside the issue of the long term stability of its orbit, the question of how this planet could form under such extreme conditions is a critical one, that might have implications on our understanding of the planet-formation process in general.

We have investigated one specific leg of the planet-formation process, the intermediate stage leading from kilometre-sized planetesimals to protoplanetary embryos, as it is the one that is probably the most affected by perturbations in close binaries. We numerically follow the evolution of one crucial parameter controlling the accreting fate of the system: the distribution of impact velocities dv amongst planetesimals orbiting HD196885A. Due to stringent computing time constraints, we adopt a deterministic model based on several simplifications (static gas disc, no disc gravity, etc.), all of which concurring to give a conservative lower limit for the dv distribution.

We find that, for almost the whole explored parameter space (planetesimal sizes, gas disc profile, inclination between the binary and the circumprimary plane, etc.),

⁶ Duchêne (2010) argues that the lower (sub)millimetre fluxes measured for discs in < 100 AU binaries do not prevent these discs from being as massive (and thus denser) as single-star ones, because such truncated discs get optically thick to their own emission (see Fig.2 of Duchêne (2010)).

impact velocities reach values that lead to eroding impacts between planetesimals. Most of the circumprimary disc is thus strongly hostile to accretion, especially the region at 2.6 AU from the primary corresponding to the current location of the planet.

We considered the possibility that the planet was formed in an accretion-friendly region much closer to the primary and later moved outward, either during the embryo accretion phase or by mutual perturbations with another (undetected) giant planet. However, we rule out this hypothesis because the inner accretion-safe region is much too narrow and close to the primary, $r \leq 0.4$ AU, to allow the formation of two giant planets.

In the highly perturbed $r \sim 2.6$ AU region, the only way for the HD196885Ab planet to form through the mutual accretion of planetesimals is either 1) if these planetesimals were initially larger than ~ 250 km, or 2) if the binary had an initial separation $a_b \geq 45$ AU and shrunk by at least a factor 2 during its early history. Although large initial planetesimals as well as early orbital compacting of binaries both make sense in view of recent planetesimal-formation and stellar cluster theories, the values we find for these 2 parameters do appear rather extreme. An alternative solution is to suppose that planetesimal grow through the so-called "snowball" growth mode (Xie et al., 2010b) by progressively sweeping up small dust particles. However, the efficiency of this alternative growth channel has not been quantitatively estimated yet, especially in the specific context of close binaries.

These results strengthen HD196885Ab's status as the most "extreme" planet-in-a-binary known to date. What sets it apart from other cases, like the γ Cephei planet or a putative habitable planet in the α Cen system, for which the canonical core-accretion scenario also encounters serious problems, is that it is the only one for which these problems could be serious enough to become insurmountable. Should this be the case, then alternative planet-formation scenarios, such as direct collapse due to disc instability, might be considered for this planet, and possibly all other giant planets in close binaries (Duchêne, 2010). Unfortunately, the disc instability scenario does also encounter severe difficulties in the context of close binaries, and it is too early to know it can be a viable alternative formation channel.

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References

- Artymowicz, P., Lubow, S. H., 1994, Dynamics of binary-disk interaction. 1: Resonances and disk gap sizes, *ApJ*, 421, 621
- Barbieri, M.; Marzari, F.; Scholl, H., 2002, Formation of terrestrial planets in close binary systems: The case of alpha Centauri A, *A&A*, 396, 219
- Beauge, C., Leiva, A. M.; Haghighipour, N.; Otto, J. Correa, 2010, Dynamics of planetesimals due to gas drag from an eccentric precessing disc, *MNRAS*, 408, 503
- Blum, Jürgen, Wurm, Gerhard, 2008, The Growth Mechanisms of Macroscopic Bodies in Protoplanetary Disks, *ARA&A*, 46, 21

- Boley, A.C., 2009, The Two Modes of Gas Giant Planet Formation, *ApJ*, 695, L53
- Boss, A.P., 2006, Gas Giant Protoplanets Formed by Disk Instability in Binary Star Systems, *ApJ*, 641, 1148
- Chambers, J.E., 2010, Planetesimal formation by turbulent concentration, *Icarus*, 208, 505
- Charnoz, S.; Thébault, P.; Brahic, A., 2001, Short-term collisional evolution of a disc perturbed by a giant-planet embryo, *A&A*, 373, 683
- Chauvin, G.; Lagrange, A.-M.; Udry, S.; Mayor, M., 2007, Characterization of the long-period companions of the exoplanet host stars: HD 196885, HD 1237 and HD 27442. VLT/NACO and SINFONI near-infrared, follow-up imaging and spectroscopy, *A&A*, 475, 723
- Chauvin, G.; Beust, H.; Lagrange, A. -M.; Eggenberger, A., 2011, Planetary systems in close binary stars: the case of HD 196885. Combined astrometric and radial velocity study, *A&A*, 528, 8
- Cieza, L.A., and 12 co-authors, 2009, Primordial Circumstellar Disks in Binary Systems: Evidence for Reduced Lifetimes, *ApJ*, 696, 84C
- Correia, A.C., and 11 co-authors, 2008, The ELODIE survey for northern extra-solar planets. IV. HD 196885, a close binary star with a 3.7-year planet, *A&A*, 479, 271
- Cuzzi, Jeffrey N.; Hogan, Robert C.; Shariff, Karim, 2008, Toward Planetesimals: Dense Chondrule Clumps in the Protoplanetary Nebula, *ApJ*, 687, 1432
- Desidera, S.; Barbieri, M., 2007, Properties of planets in binary systems. The role of binary separation, *A&A* 462, 345-353
- Duchêne, G., 2010, Planet Formation in Binary Systems: A Separation-Dependent Mechanism?, *ApJ*, 709, L114
- Duquennoy, A.; Mayor, M., 1991, Multiplicity among solar-type stars in the solar neighbourhood. II - Distribution of the orbital elements in an unbiased sample, *A&A*, 248, 485
- Dvorak, R.; Pilat-Lohinger, E.; Funk, B.; Freistetter, F., 2003, Planets in habitable zones: A study of the binary Gamma Cephei, *A&A*, 398, L1
- Fragner, M.; Nelson, R.; Kley, W., 2011, On the dynamics and collisional growth of planetesimals in misaligned binary systems *A&A*, 528, 40
- Goodchild, Simon; Ogilvie, Gordon, 2006, The dynamics of eccentric accretion discs in superhump systems, *MNRAS*, 366, 973
- Guedes, J.M.; Rivera, E.J.; Davis, E.; Laughlin, G.; Quintana, E.V.; Fischer, D.A., 2008, Formation and Detectability of Terrestrial Planets around alpha Centauri B, *ApJ*, 679, 1582
- Haghighipour, Nader; Dvorak, Rudolf; Pilat-Lohinger, Elke, 2010, Planetary Dynamics and Habitable Planet Formation in Binary Star Systems, *ASSL*, 366, 285
- Hale, A., 1994, Orbital coplanarity in solar-type binary systems: Implications for planetary system formation and detection, *AJ*, 107, 306
- Hatzes, A.P.; Cochran, W. D.; Endl, M.; McArthur, B.; Paulson, D.B.; Walker, G.A.H.; Campbell, B.; Yang, S., 2003, A Planetary Companion to Gamma Cephei A, *ApJ*, 599, 1383
- Hayashi, C., 1981, Structure of the Solar Nebula, Growth and Decay of Magnetic Fields and Effects of Magnetic and Turbulent Viscosities on the Nebula, *PthPS* 70, 35

- Heppenheimer, T.A., 1978, On the formation of planets in binary star systems, *A&A*, 65, 421
- Holman, M.J., Wiegert, P. A., 1999, Long-Term Stability of Planets in Binary Systems, *AJ*, 117, 621
- Jang-Condell, H.; Mugrauer, M.; Schmidt, T., 2008, Disk Truncation and Planet Formation in Gamma Cephei, *ApJ*, 683, L191
- Johansen, Anders; Oishi, Jeffrey S.; Mac Low, Mordecai-Mark; Klahr, Hubert; Henning, Thomas; Youdin, Andrew, 2007, Rapid planetesimal formation in turbulent circumstellar disks, *Nature*, 448, 1022
- Kley, W., Nelson, R. P., 2007, in "Planets in binary Star Systems," ed. Nader Haghighipour (Springer publishing company)
- Kley, W., Nelson, R. P., 2008, Planet formation in binary stars: the case of Gamma Cephei, *A&A*, 486, 617
- Kokubo, E., Ida, S., 2000, Formation of Protoplanets from Planetesimals in the Solar Nebula, *Icarus*, 297, 1067
- Lagrange, A.-M.; Beust, H.; Udry, S.; Chauvin, G.; Mayor, M., 2006, New constraints on Gliese 86 B. VLT near infrared coronagraphic imaging survey of planetary hosts, *A&A*, 459, 955
- Lissauer, J.J., 1993, Planet formation, *ARA&A*, 31, 129
- Lithwick, Yoram; Chiang, Eugene, 2007, Collisional Particle Disks, *ApJ*, 656, 524
- Makino, J., Fukushima, T., Funato, Y., Kokubo, E., 1998, On the mass distribution of planetesimals in the early runaway stage, *NewA*, 3, 411
- Malmberg, D.; Davies, M. B.; Chambers, J. E., 2007, Close encounters in young stellar clusters: implications for planetary systems in the solar neighbourhood, *MNRAS*, 378, 1207
- Marzari, F., Scholl, H., 2000, Planetesimal Accretion in Binary Star Systems, *ApJ*, 543, 328
- Marzari, F., Thebault, P., Scholl, H., 2008, Planetesimal Evolution in Circumbinary Gaseous Disks: A Hybrid Model, *ApJ*, 681, 1599
- Mayer, Lucio; Wadsley, James; Quinn, Thomas; Stadel, Joachim, 2005, Gravitational instability in binary protoplanetary discs: new constraints on giant planet formation, *MNRAS*, 363, 641
- Minton, David A.; Malhotra, Renu, 2010, Dynamical erosion of the asteroid belt and implications for large impacts in the inner Solar System, *Icarus*, 207, 744
- Morbidelli, A.; Bottke, W. F.; Nesvorný, D.; Levison, H. F., 2009, Asteroids were born big, *Icarus*, 204, 558
- Mugrauer, M.; Neuhäuser, R., 2009, The multiplicity of exoplanet host stars. New low-mass stellar companions of the exoplanet host stars HD 125612 and HD 212301, *A&A*, 494, 373
- Nelson, Andrew, 2000, Planet Formation is Unlikely in Equal-Mass Binary Systems with $a = 50$ AU, *ApJ*, 537, 65
- Neuhäuser, R.; Mugrauer, M.; Fukagawa, M.; Torres, G.; Schmidt, T., 2007, Direct detection of exoplanet host star companion Gamma Cep B and revised masses for both stars and the sub-stellar object, *A&A*, 462, 777
- Paardekooper, S.-J., Thébault, P., & Mellema, G., 2008, Planetesimal and gas dynamics in binaries, *MNRAS*, 386, 973

- Paardekooper, S.-J., Leinhardt, Z.M., 2010, Planetesimal collisions in binary systems, *MNRAS*, 403, L64
- Payne, M.J., Wyatt, M.C., Thebault, P., 2009, Outward migration of terrestrial embryos in binary systems, *MNRAS*, 400, 1936
- Plavchan, P.; Werner, M.W.; Chen, C.H.; Stapelfeldt, K.R.; Su, K.Y. L.; Stauffer, J.R.; Song, I., 2009, New Debris Disks Around Young, Low-Mass Stars Discovered with the Spitzer Space Telescope, *ApJ*, 698, 1068
- Queloz, D.; Mayor, M.; Weber, L.; Blécha, A.; Burnet, M.; Confino, B.; Naef, D.; Pepe, F.; Santos, N.; Udry, S., 2000, The CORALIE survey for southern extra-solar planets. I. A planet orbiting the star Gliese 86, *A&A*, 354, 99
- Quintana, E. V., Adams, F. C., Lissauer, J.J., Chambers, J. E. 2007, *ApJ*, 660, 807
- Savonije, G. J.; Papaloizou, J. C. B.; Lin, D. N. C., 1994, On Tidally Induced Shocks in Accretion Discs in Close Binary Systems, *MNRAS*, 268, 13
- Stewart, Sarah T.; Leinhardt, Zoë M., 2009, Velocity-Dependent Catastrophic Disruption Criteria for Planetesimals, *ApJ*, 691, L133
- Takeuchi, T., Lin, D.N.C., 2002, Radial Flow of Dust Particles in Accretion Disks, *ApJ*, 581, 1344
- Teiser, J.W., Wurm, G., 2009, High-velocity dust collisions: forming planetesimals in a fragmentation cascade with final accretion, *MNRAS*, 393, 1584
- Thebault, P., Augereau, J. C., 2007, , Collisional processes and size distribution in spatially extended debris discs, *A&A*, 472, 169
- Thebault, P., Brahic, A., 1998, Dynamical influence of a proto-Jupiter on a disc of colliding planetesimals, *P&SS*, 47, 233
- Thebault, P., Marzari, F., Scholl, H., 2006, Relative velocities among accreting planetesimals in binary systems: The circumprimary case, *Icarus*, 183, 193
- Thebault, P., Marzari, F., Scholl, H., Turrini, D., Barbieri, M., 2004, Planetary formation in the Gamma Cephei system, *A&A*, 427, 1097
- Thebault, P., Marzari, F., Scholl, H., 2008, Planet formation in alpha Centauri A revisited: not so accretion friendly after all, *MNRAS*, 388, 1528
- Thebault, P., Marzari, F., Scholl, H., 2009, Planet formation in the habitable zone of alpha Centauri B, *MNRAS*, 393, L21
- Weidenschilling, S., Davis, D. R., 1985, Orbital resonances in the solar nebula - Implications for planetary accretion. *Icarus*, 62, 16
- Xie, Ji-Wei; Zhou, Ji-Lin, 2008, Planetesimal Accretion in Binary Systems: The Effects of Gas Dissipation, *ApJ*, 686, 570
- Xie, Ji-Wei; Zhou, Ji-Lin, 2009, Planetesimal Accretion in Binary Systems: Role of the Companion's Orbital Inclination , *ApJ*, 698, 2066
- Xie, Ji-Wei; Zhou, Ji-Lin, Ge, Jian, 2010, Planetesimal Accretion in Binary Systems: Could Planets Form Around alpha Centauri B?, *ApJ*, 708, 1566
- Xie, Ji-Wei; Payne, Matthew J.; Thebault, Philippe; Zhou, Ji-Lin; Ge, Jian, 2010, From Dust to Planetesimal: The Snowball Phase?, *ApJ*, 724, 1153
- Zsom, Andras; Sandor, Zsolt; Dullemond, Cornelis, 2011, The first stages of planet formation in binary systems: how far can dust coagulation proceed?, *A&A*, 527, 10
- Zucker, S.; Mazeh, T.; Santos, N.C.; Udry, S.; Mayor, M., 2004, Multi-order TODCOR: Application to observations taken with the CORALIE echelle spectrograph. II. A

planet in the system HD 41004, A&A, 426, 695